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Publication date:
2015

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Citation (APA):

Christensen, J. M., Pacino, D., Fonseca, J. F. P., & Psaraftis, H. N. (2015). *Cargo-mix optimization in Liner Shipping*. Abstract from Odysseus 2015; Sixth International Workshop on Freight Transportation and Logistics, Ajaccio, Corsika, France.

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Cargo-mix optimization in Liner Shipping

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Keywords: *Maritime Logistics, Stowage Planning, Metaheuristic.*

1 Introduction

International transportation constitutes one of the biggest challenges in limiting CO₂ emission in the world: It is technically hard to find viable alternatives to fossil fuels, and due to the international nature, it is very difficult to regulate CO₂ emission of intercontinental trade. Moreover, it is hard to motivate companies to pay for cleaner transport since transportation is not visible to end customers, and therefore cannot justify a higher cost. Hence, optimization may be one of the few options for limiting CO₂ emission of international trade. A possible direction is to focus on vessels' utilization. The more containers a vessel carries the smaller is the resulting CO₂ emissions per transported ton of cargo. This is what can be seen as a win-win situation. Better vessel utilization will result both in cleaner transport and in better revenue margins for the shippers.

Focus on vessel intake maximization is no news for liner shippers. Container vessels are delivered with a nominal capacity that ship owners know is only theoretical. Unless the cargo weight distribution is perfect, the nominal intake cannot be reached. Stowage coordinators fight this battle everyday. They are the planners of the cargo and have to find a load configuration (*stowage plan*) that both suits the current cargo to be loaded but also guarantees that the vessel can be utilized to its maximum in future ports. The size of nowadays vessels is, however, making this work harder and harder (Pacino et al. (2011)). Moreover, the cargo composition available in the different ports might not be suitable for the full utilization of the vessel. To give a very brief example, consider a vessel that has to load a high number of very heavy containers. As a consequence the *draft* of the vessel (the distance between the waterline and the bottom of the hull) will be greater. If the vessel has to visit a port with a lower draft, stowage coordinators will have to leave a number of containers behind in order to reduce the draft. This is clearly not a desirable situation. The focus of our work is the analysis of vessels' cargo-mix, in particular finding what cargo composition is needed for a vessel to maximize its utilization on a given service. Such a model can have various applications ranging from driving rates prices, improving fleet composition and network design ((Christiansen et al., 2007; Reinhardt and Pisinger, 2012; Brouer et al., 2014)). Also the model could be used to analyze the impact of an expected cargo load compared to the optimal one.

Optimizing the intake of a vessel requires deep understanding about vessel architecture. Loading plans must make sure that the vessels can sail safely also in rough weather conditions. The cargo-mix problem is tightly connected to the stowage planning problem. In stowage planning, a list of container to be loaded is given (Pacino et al. (2011)), while in cargo-mix the selection of containers to load is only limited by the expected cargo flows of the analyzed service (Delgado (2013)). All the stability and staking constraints are, however, the same between the two problems, thus ideas from the stowage planning literature should be taken into account.

2 The liner shipping cargo-mix problem

Given a liner service, a vessel and the expected cargo flows, the liner shipping cargo-mix problem aims at finding an optimal cargo-mix for the vessel at each port of call which fulfills the stability requirements, respects the expected cargo flows, minimizes overstowage and maximized the cargo intake. Overstowage occurs when a container destined to a later port is stowed above a container to be discharged at an earlier port.

When stowing a container vessel there are numerous constraints that must be satisfied for the vessel to be deemed sea worthy. Stacking rules impose e.g. that 20-foot containers cannot be stowed on top of 40-foot ones, that refrigerated containers (*reefers*) must be stowed where power plugs are available. The weight of the container stacks must also be within limits. Line of sight rules and the presence of hatch-covers (metallic structures dividing the on and below deck part of a vessel) also impose height limits on the stacks. This last rule is particularly important due to the presence of high-cubes, containers higher than the standard 8.6 foot.

Stacking rules are not enough to ensure the sea worthiness of a vessel. The weight distribution on the vessel must obey the hydrostatics of the vessel. The more weight we load on the vessel the deeper a draft it will have. The draft must be within the operational limits of the ports the vessel will visit. Consider now Figure 1 (a). The difference between the draft at stern and at bow is called *trim* which must be within limits to ensure safe sailing. Figure 1 (b) shows the transversal section of a vessel. The distance between the point M (*metacenter*) and the point G (the center of gravity) is called *metacentric height*. The metacentric height must also be within operational limits to ensure that the vessel will not capsize. Moreover stress forces such as *shear forces* and *bending moments* must also be held at bay.

Implementing an optimization model that does not take all of those requirements into account will not be able to accurately calculate the optimal intake of a vessel. This poses a challenge. Assume we allow to stow one extra container on each stack due to an imprecise calculation. Given the size of today's vessel this will result in an error of ca. 1000 containers.

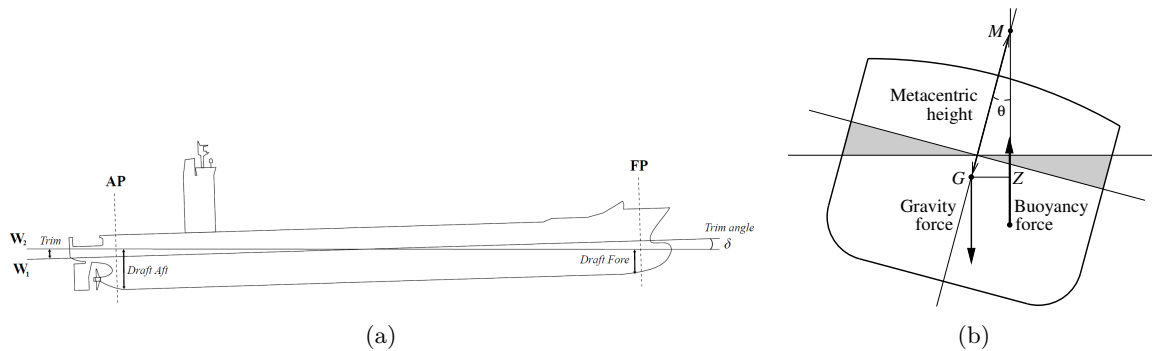


Figure 1: Vessel stability; trim, draft and metacentric height.

3 Approach

Academic work on the liner shipping cargo-mix problem is very limited. The first formal description was presented in the Ph.D. thesis of Delgado (2013). A integer programming model was presented. In order to achieve scalability, the author proposes the same decomposition as in earlier stowage

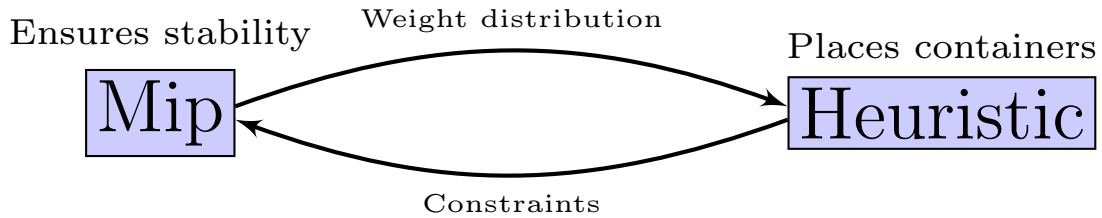


Figure 2: *An illustration of the solution method and the information passed between the two different modules.*

planning work (Pacino et al. (2011)). Tested on 360 instances, on a services of up to 10 ports, the approach was able to solve 91.7% of the instances, with a time limit of 60 minutes. The application of the model, however, requires faster solving times since the problem must be solved several times so that different scenarios and analysis can be done. This motivates our effort on identifying an efficient heuristic procedure that can reach near optimal solutions in very short times.

As previously described the cargo-mix problem shares great similarities with stowage planning, thus related methods can be used as inspiration. State-of-the-art stowage planning approaches (Pacino et al., 2011; Wilson and Roach, 1999; Kang and Kim, 2002; Ambrosino et al., 2010) use multi-phase methods. An initial phase solves the master bay planning problem in which groups of containers are assigned to specific subsections on the vessel. The second phase solves the slot planning problem that independently solve each of the subsections assigning containers to a specific positions. Methods related to the master bay planning problem are of particular interest, since, as mentioned by Delgado (2013) and Pacino et al. (2011), slot planning does not have a strong impact on the final solution and can be disregarded when we only need the analysis of aggregated results, such as it is for the cargo-mix problem. Heuristic methods, for the master bay planning problem are not many and they either focus on the vessel stability (e.g. Min et al. (2010)) or on the container distribution on a single port (e.g. Ambrosino et al. (2010); Xiao (2009)). Our hypothesis is that the stability requirements and the multi-port nature of the problem makes the discovery of heuristic rules difficult. In this work we are trying to combine what we have learned from the literature. Stability requirements are easily satisfied by linear programming (Pacino et al. (2011)), while actual container distribution requires heuristic methods (Ambrosino et al. (2010)). With this in mind, we proposed the iterative two-phase approach for the liner shipping cargo-mix problem depicted in Figure 2. Initially the algorithm ensures the feasibility of the stability constraints solving a mixed integer linear programming model that distributes the weight along the vessel. This ensures that the vessel is seaworthy and that stress forces are within limits. Successively a heuristic procedure tries to find a container assignment that follows the given weight distribution. The resulting cargo-mix is then analyzed and parts of the vessel are allowed to diverge from the original weight distribution if they can improve the vessel intake. Those deviations are then sent back to the mixed integer linear program in the form of constraints. The idea is to iteratively use the linear program as guidance for the satisfiability of the stability constraints.

4 Preliminary Results

The proposed heuristic has been tested on 24 diverse instances, each with varying number of containers available. In all the tests the vessel used has a capacity of approximately 15000 TEUs. The results have been compared with an upper bound found by a linear relaxation of a slightly modified

model of the one presented in Delgado (2013).

Table 1 shows the result. The table contains the upper bound found by the LP-relaxation, the heuristic solution, the Gap in percentage, and the time used by the heuristic. The heuristic is run 10 times per instance, and the table reports the average values.

Instance	Ub	x	Gap %	t (s)	Instance	Ub	x	Gap %	t (s)
I01	76822	65771	14%	13.4	I13	99101	82463	17%	10.9
I02	76798	66443	13%	11.4	I14	99069	82309	17%	11.3
I03	76820	66382	14%	12.2	I15	99354	82406	17%	11.1
I04	99132	82407	17%	10.5	I16	168959	122042	28%	9.5
I05	98941	82477	17%	10.8	I17	168766	121046	28%	9.9
I06	99349	82620	17%	10.7	I18	169227	121688	28%	9.7
I07	101804	83943	18%	11.0	I19	193207	136816	29%	9.1
I08	101687	84189	17%	11.5	I20	193099	135814	30%	9.0
I09	101611	83701	18%	10.9	I21	192994	136779	29%	8.5
I10	97658	80989	17%	12.0	I22	208330	150589	28%	8.9
I11	97673	81192	17%	10.8	I23	208051	148136	29%	9.6
I12	97684	80821	17%	11.3	I24	208280	149534	28%	8.4

Table 1: *Results table. The instance column is the instance name, Ub is the upper bound, x denotes the average solution value found by the heuristic. Gap denotes the gap between the average solution and the upper bound. t is the average time spent in second for the heuristic.*

Table 1 shows that the heuristic is able to find feasible solutions within 10 seconds time, however the quality of these solutions is far from the upper bound. Thus more work is needed to achieve better solutions.

During the talk we wish to present a more concrete description of the algorithm. As future work we see the integration of the stochasticity of the cargo flows and possibly including the cargo-mix problem as part of a different decision process e.g. service network design.

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